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MOLTEN SALT REACTORS AND THEIR DEVELOPMENT OVER THE YEARS - A REVIEW

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ABSTRACT

This paper briefly reviews the molten salt reactor (MSR) concept and explains the key technology innovations that have revived the very concept in the 2000s since the 1960s. The paper compares the origin of the molten-salt reactor concept and how the encouraging results of the aircraft reactor program led to the recognition of the potential of MSR for economical generation of electricity. The role of the MSR experiment was to demonstrate the practicality of this high-temperature fluid-fuel concept which seemed so promising on the basis of materials compatibility information and calculated fuel cycle costs.

This paper also describes and compares the reactors itself, including the fuel composition, diagram structure, moderators, materials, cost, efficiency, and layout. It further examines the safety hazards overcome in the advanced molten state reactors due to improvements in technology.A review is further extended to the key technology innovations in Transatomics Power's (TAP) advanced MSR followed by the design pathway chosen instead of a thorium-fuelled reactor. It gives us a comparative analysis which concludes that the advanced MSR being used by TAP proves to be superior to other light water reactors (LWR) by significantly reducing waste.

KEY WORDS: Molten Salt Reactor (MSR), Transatomics Power's & Thorium-Fuelled Reactor

A Review

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INTRODUCTION

MSRs have been in existence since the 1960s, but it is still not used to its full potential and the research regarding the large-scale use of these reactors has been limited. But since the 1960s there has been a lot of progress to make the reactor safe, reliable, and maintainable. MSRs have many safety benefits over traditional LWRs and other conventional reactors such as the passive shutdown ability, low-pressure piping, negative void and chemically stable coolant. The greater part of the early work on these plans concentrated on component lifetime, specifically, creating composites ready to keep up their mechanical and material integrity in a corrosive, radioactive salt condition. Despite this advance, the world stayed concentrated on LWRs or Heavy Water Reactors (HWR) for commercial use, essentially because of broad past operating experience with naval water-cooled reactors and early commercial reactors [1]. The modern designs have greatly improved molten salt concepts while significantly retaining its safety benefits. In Molten Salt Reactor Experiment (MSRE) the fuel in the salt is primarily uranium. Modern-day reactors use low-enriched uranium (LEU) fuel at the commercially-available enrichment of 5%, far lower than other reactor designs. Previous MSRs such as the Oak Ridge National Laboratory (ORNL) relied on high-enriched uranium, with enrichments up to 93% U-235 [2]. Enrichments that high would raise proliferation

concerns if used in commercial nuclear power plants.

Diagram Structure

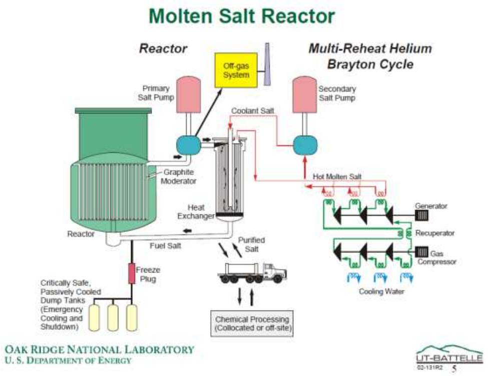

Figure 1: Molten Salt Reactor Experiment, Oak Ridge National Laboratory (1960s) [3]

figure 1 shows the schematic diagram of the MSRE structured. It has a small core-reactor to have maximum neutron leakage and there is no blanket of fertile material. The fuel salt was specifically made without thorium as the reactor was built to be a 2-fluid breeder. The MSRE had the normal operating conditions at 8 MW, the maximum capacity at which the air-cooled secondary heat exchanger can operate. The building housing the reactor is the one in which the Aircraft Reactor Experiment was operated in 1954. The cylindrical reactor cell was added to the Aircraft Reactor Test (which was decommissioned) and was later adapted for MSRE usage.

The core is made of graphite bars, exposed to the fuel. The control rods are adaptable, comprising of a hollow cylinder of Gd2Os-Al2Os clay, canned in Inconel and strung on a stainless-steel hose which additionally fills in as a cooling-air conduit. The rods are raised and lowered simultaneously. A filtration bed having pipes with charcoal is submerged in a water-filled tank. All salt vessels are electrically warmed so that the salt is in the molten state, even though no nuclear energy is produced. The reactor vessel furnace covers with thick heater shield made of stainless steel and steel balls and water for cooling. The shield absorbs most of the energy of neutrons and gammas escaping the reactor vessel. All the components in the reactor and drain tank cells are designed and laid out so they can be removed by the use of long-handled tools from above. In the same building, adjacent to the drain-tank cell, there is a simple facility for processing the fuel for flush salt [4]. It was shown in Figure 2.

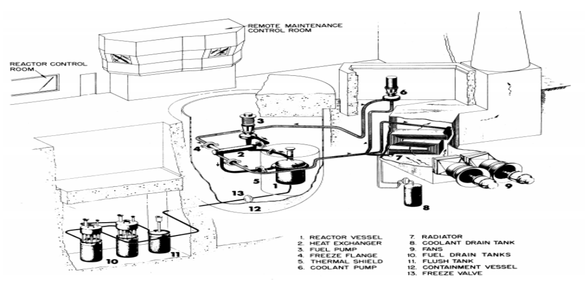

Figure 2: Layout of MSRE [4]

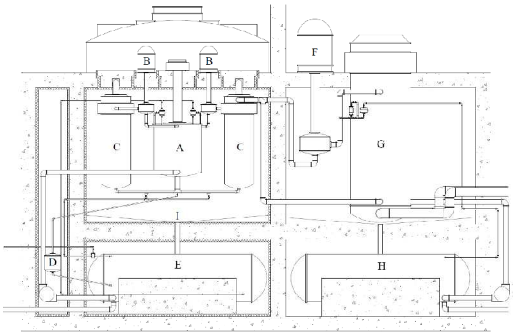

Figure 3: TAP's Design for Advanced Molten Salt Reactors [1]
A) Reactor Vessel, B) Fuel Salt Pumps, C) Primary Heat Exchangers
D) Freeze Valve, E) Primary Loop Drain Tank, F) Intermediate Loop Salt Pump
G) Steam Generator, H) Intermediate Loop Drain Tank, and I) Fuel Catch Basin

Figure 3 shows a reactor's primary loop consists of the reactor vessel, moderator, pumps, and primary heat exchanger. The pumps function to circulate the fuel salt through the loop. The heat generated in this process in the primary stage is transferred via heat exchangers into an intermediate loop filled with molten salt. This then proceeds to transfer the heat to the steam generators, adding an extra layer protection against radioactive release. The generators proceed to use the heat to boil water into steam, which is then fed into a building with the turbine.

Various Fuels for Reactors

Commercial usage of current nuclear power plants for fuels is solid uranium oxide fuel in the form of pellets, surrounded by metal cladding (acts as a barrier as well as shielding).

In the current form of plant uses liquid fuel instead, with uranium dissolved in a molten fluoride salt. The salt acts as both fuel and coolant, which provides better economic standard as well as efficiency [1].

Higher Outlet Temperatures

From the figure 4, it is observed that the use of liquid fuels permits better heat transfer, this, in turn, gives higher reactor outlet temperatures; which in turn leads to higher thermal efficiency.

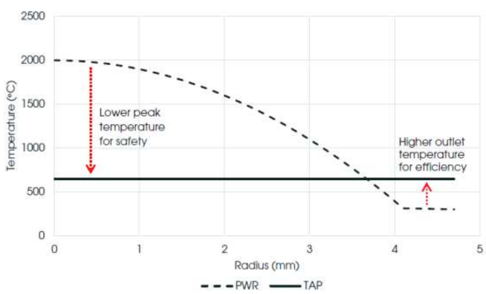

Figure 4: Temperature Profile of LWR Solid Fuel Pin, from Centre to Edge, Compared to the Temperature Profile of a TAP MSR Fuel-Salt [1]

Zirconium Hydride Moderator

A defining difference in this particular reactor and other MSR is the use of zirconium hydride moderator instead of a regular graphite moderator. The graphite moderator shrinks and swells over time due to irradiation, these dimensional changes reduce the mechanical integrity [2]. This meant the replacement of the moderator every 4 years.

The Zirconium Hydride moderator rods have mentionable changes under irradiation [5]. Upon that they possess lower neutron absorption and high resistance to radiation damage. figure 5 shows the moderator design.

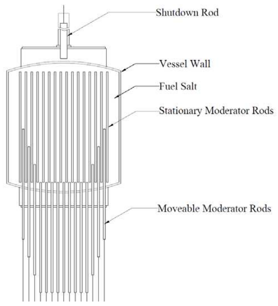

Figure 5: Moderator Design [1]

Safety Measures

Historically, Nuclear power plants have two big problems: they produce radioactive nuclear waste and they can be vulnerable to a disaster like a nuclear meltdown. Nuclear meltdowns happen because water that's used to cool the radioactive fuel rods cannot be pumped in, usually due to backup power failure. This heats up the fuel rapidly and resulted in explosions.

But safety is not just about stopping disasters. The fuel itself is toxic and has to store underground for thousands of years. The solid fuel can only stay in the reactor for a limited amount of time before it starts to break itself down and needs to physically remove. We can only extract about 4% of the energy that could be conceivably got out of uranium and the rest is left behind as waste.

The critical safety and licensing issues are one of the most important factors to be considered while comparing power plants. MSRs are Generation IV nuclear fission reactors with potentially superior safety. The major factors taken into account are Decay Herat Removal, Source Term, and neutrons. MSRs have a different Decay Heat Approach as they dump fuel salt to tanks. Moreover, the actinides and fission products in the solution play a key role in the safety of the reactor.

Low pressure (a molten salt boiling point is about 1400^{o}C), Low chemical reactivity, low accident source term with continuous removal of mobile fission products and passive cooling by dumping fuel into cooled tanks which includes facilities for emergency cooling and shutdown has led to an exponential increase in safety. Reduced radionuclide source term, limited release of radionuclides under reactor conditions due low iodine and cesium release potential have contributed immensely to the increasing safety over the past couple of decades.

In spite of having small accident sources in the reactor, there has been a rise in the probability of an accident due to the Off-Gas system, specifically the safety issues of spent nuclear fuel (SNF) processing plants. It was concluded that while the reactor can achieve criticality on SNF fuel load and on SNF fuel feed, it cannot maintain criticality for sufficient lengths of time to produce a sustainable net-negative waste profile.

Transatomic's reactor design will use the fuel in a liquid form so that it can stay in the reactor for a longer period of time thereby directly leaving significantly less waste behind. Use of fuel pebble instead of conventional uranium rods has been used. This new design encases uranium in a golf-sized sphere. It's made of a very strong ceramic material that can withstand much higher temperatures, so it cannot melt and is safer to use. The following are the points which have

resulted in the better inherent safety of Transatomic's MSR[1].

Self-Stabilizing Core

Like LWRs, MSRs have a strongly negative void and temperature coefficients. These negative coefficients greatly aid reactor control and act as a strong buffer against temperature excursions. As the core temperature increases, the salt expands. When the salt expands the density of the fissile material is reduced, slowing down the fission rate without operator intervention. Additionally, U-238's neutron capture cross section also increases with temperature due to the Doppler Effect.

Smaller Inventory of Radio Nuclides

As TAP's designs produce higher thermal efficiency, the fissile material needed for the reactors is less. The reduction in noble gases, noble metals and lanthanides reduce the maximum size of a potential release.

Reduced Driving Force

The demand for the fuel salt to be kept under high pressure is non-existent because of its chemical properties. Additionally, rupture disk technology is used to protect against upstream pressure transients. Therefore, there is no requirement of a large driving force. The TAP MSR is more advanced than LWRs because it is walkways safe and can passively cool its drained core via cooling stacks connected to its auxiliary tank. In case of failure of the freeze valve the shutdown rod is inserted using an electromagnetic fail-safe or by operator action, avoiding an explosion. If these measures can't be used the salt temperature increases. This excess heat causes the salt to expand reducing reactivity. If the temperature keeps on increasing the zirconium hydride moderator starts melting (Releasing small amounts of hydrogen not enough to cause an explosion). The lack of sufficient neutron moderation because of the reduced moderator area brings the reactor to a sub-critical state. figure 6 shows the key temperatures for an LWR and a TAP MSR.

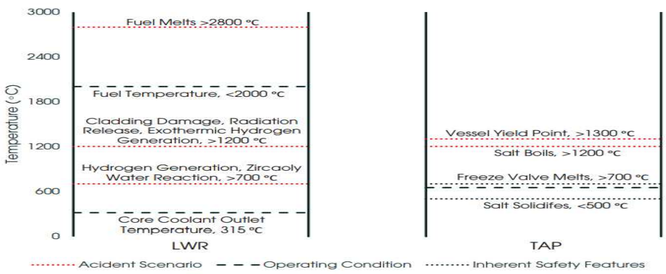

Figure 6: Key Temperatures for an LWR and a TAP MSR [1]

Thorium as Fuel

Though thorium fuel cycle has theoretical advantages over uranium over the long run, primarily we use uranium because of many constraints.

One of the primary concerns is safety as thorium reactors contain plutonium; they do have potential proliferation vulnerabilities because of the protactinium in their fuel salt. Protactinium has a high neutron capture cross-section and, in this manner, in most fluid thorium reactor plans, it must be expelled consistently from the reactor. This procedure yields generally unadulterated protactinium, which at that point decays into U-233. By plan, the pure U-233 is sent over into the reactor where it is signed as its essential fuel. The downside, nonetheless, is that U-233 is a weapons-grade isotope that is

much easier to trigger than plutonium [1].

The feasibility of chemical reprocessing is the second concern as some processes are too difficult to be implemented. This can have several causes: “the processes considered are not well understood or mastered, the flow of materials to be processed is too large, the reprocessing implies direct coupling to the reactor core” [6].

It is important to maintain the breeding ratio of the reactor to be equal to 1 for fuel regeneration capability to be constant. “The breeding ratio expresses the balance between the creation of ^{233}U through neutron capture on ^{232}Th and the destruction of ^{233}U through fission or neutron capture.” If it is less than 1, the more fissile matter must be fed constantly to the reactor core. If it is greater than 1, there are excess fissile matter and it damages the reactor core. Hence, in both the cases, it costs the user of a lot of money [6].

Materials lifespan is another issue. This concerns how the graphite reacts to irradiation exposure. Beyond a certain degree of damage, it becomes the seat of swelling. With this constraint, we seek to avoid replacing the core graphite too frequently [7].

Some may avoid thinking about the proliferation risk of the thorium fuel cycle because the U-233 in the reactor would be mixed with U-232, making it a poor source for proliferation purposes. However, it is the decay products of U-232 that produce high-energy gamma radiation that makes it difficult to handle. It is impossible to handle the products in the reactors leaving weapons-grade uranium.

CONCLUSIONS

Transatomic Power’s designs have made significant changes to the existing designs and have made use of the basic technology behind the idea persists. The significant differences between the pre-existing reactors and Tran’s atomic power reactors are stated above and it achieves high actinide burn up and a cost-effective design. Unlike other reactors in the industry, the TAP MSR has a thermal/epithermal spectrum, which reduces neutron damage to the moderator and other plant components, consequentially lowering the costs associated with component replacement hence there is no need for constantly changing the zirconium hydride moderator. This reactor is also proliferation resistant because thorium and its risks are avoided. And also, the safety of the plant is drastically improved as stated above. The TAP MSR addresses some of the most pressing problems facing the nuclear industry such as safety, waste, proliferation, and cost. This very clearly shows the MSR is better than LWRs in all respects.

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